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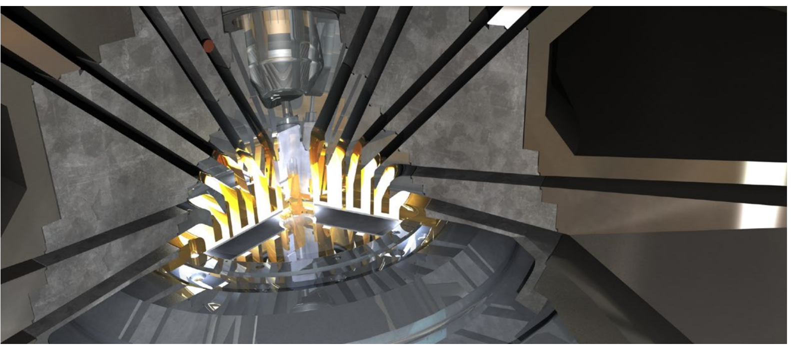

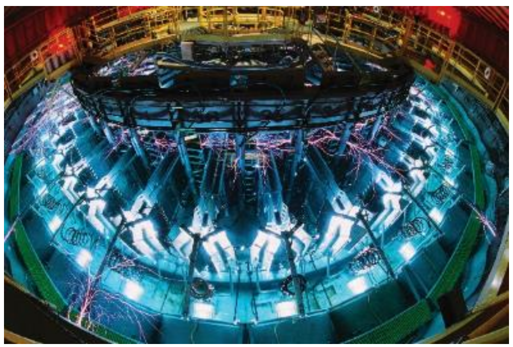

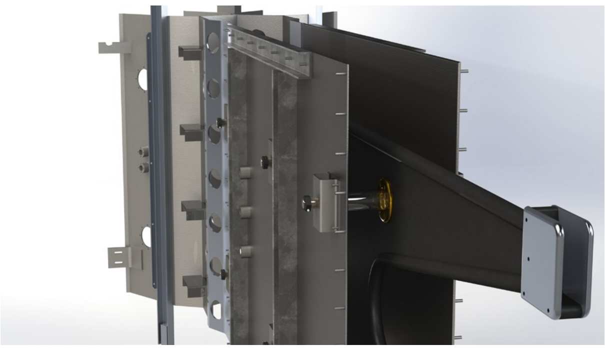

The Saturn Accelerator Recapitalization Project

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Presented at the 2020 EAPPC/Beams, Aug. 29, 2021

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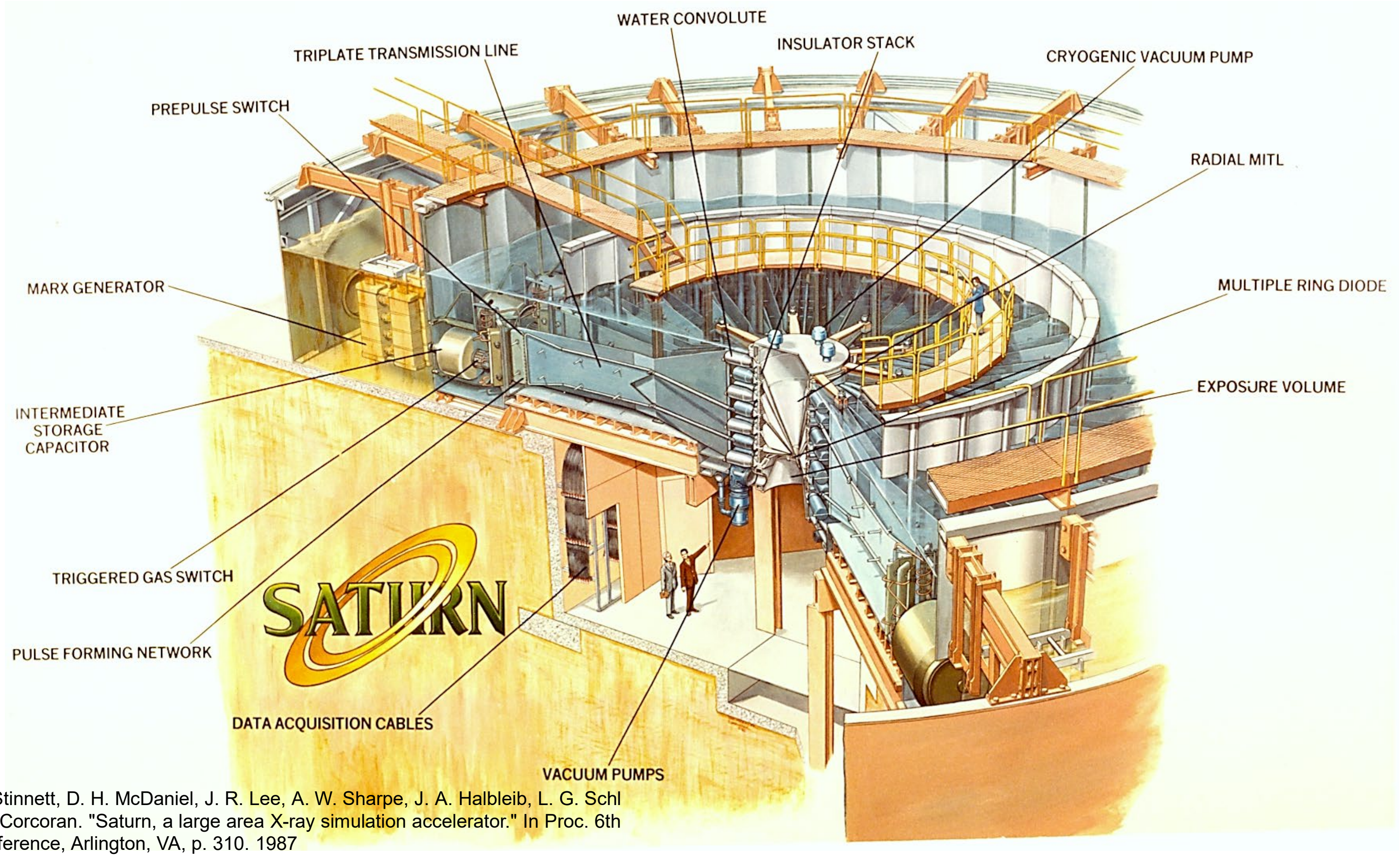
Saturn Pulsed Power Overview: A High Current Accelerator for X-ray Radiation Effects Science and Testing[1]

- Predecessor to 'Z'
- Modular, high-power, variable-spectrum, pulsed-power accelerator (10 MA, 1.6 MeV,40 ns power-pulse and ~25ns radiation pulse width)
- High dose-rate generator for 1.6MeV endpoint bremsstrahlung x-rays

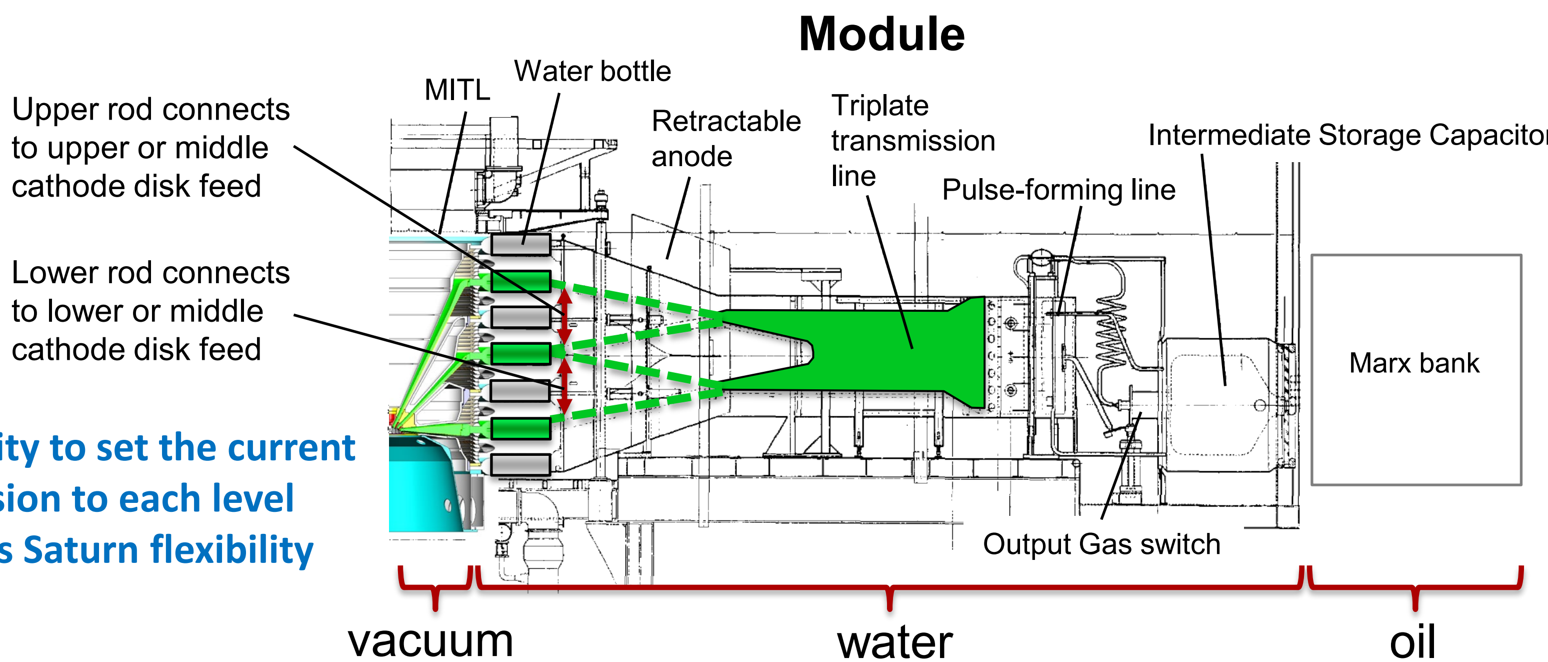


1. D.D. Bloomquist, R. W. Stinnett, D. H. McDaniel, J. R. Lee, A. W. Sharpe, J. A. Halbleib, L. G. Schlitt, P. W. Spence, and P. Corcoran. "Saturn, a large area X-ray simulation accelerator." In Proc. 6th IEEE Pulsed Power Conference, Arlington, VA, p. 310. 1987

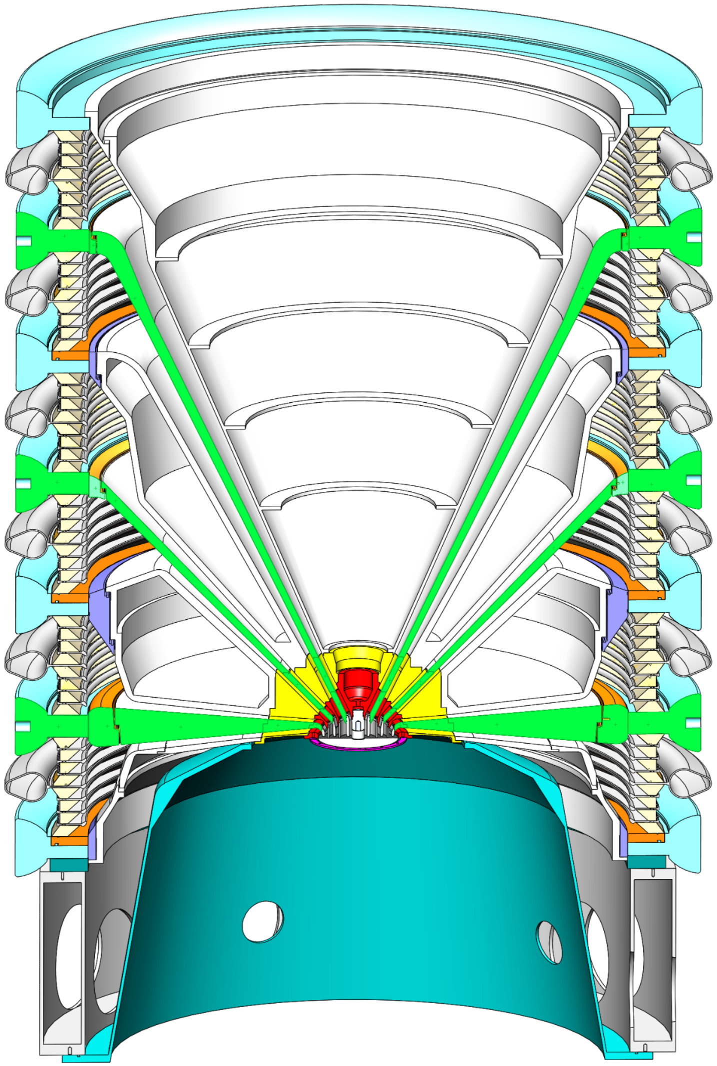
The Saturn Architecture

- 36-module, cylindrical geometry
  - ~40 kJ, 1 TW per module
  - ~2 MV at beginning of TL
  - 40 ns FWHM power pulse
  - Nominally 2 Ω
  - Anode is grounded, cathode is pulsed negative
- Water convolute connects lines to vacuum stack
  - Each line is connected to two 8 Ω rods
  - Each rod connects to ½ Ω radial cathode disk feed in water
  - Up to 36 rods (half machine) can be connected to each level

Ability to set the current division to each level gives Saturn flexibility



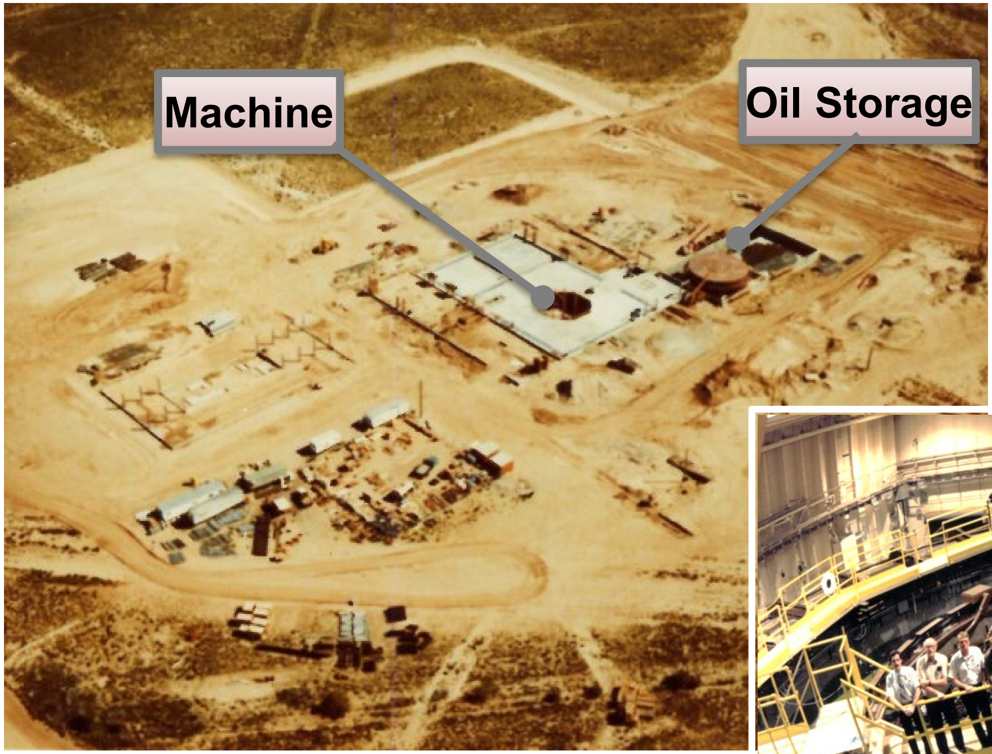
The Vacuum Stack, MITL and load region of the baseline configuration



- 3 nested conical triaxial lines, each making an anode-cathode-anode pair
- Bottom 2 lines are 2 Ω driven by 36 rods in azimuth
- Middle two lines are 3 Ω driven by 24 rods in azimuth
- Top two lines are 6 Ω driven by 12 rods in azimuth
- Each conical electrode is made in three sections
- Replacing relatively small hardware close to the axis allows a variety of loads to be fielded

Original Infrastructure is nearly 45 year old.

The Particle Beam Fusion Accelerator (PBFA-1) was the predecessor for Saturn



1977
Ariel View of PBFA I Building & Infrastructure Under Construction

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PBFA I on line in 1981: energy storage section & technical utility systems date to here.

PBFA-1 was converted to Saturn in 1987

1987
Team Photo Following PBFA I Conversion to Saturn

Pulse forming, transmission, and power flow sections date to here.

Bottom line…

- Issues

  The facility is aged and operating in a run-to-failure mode with significant deferred maintenance

  Present research and development in radiation sciences are stressing the capability

  - Insufficient shot frequency to cover requests
  - No time to address deferred maintenance
  - Shot to shot irreproducibility

  Development of new platforms and future R&D cannot be realized

- Maintenance and Refurbishment Assessment

  ~ 160 risk-prone scenarios are currently identified related to operations & infrastructure.

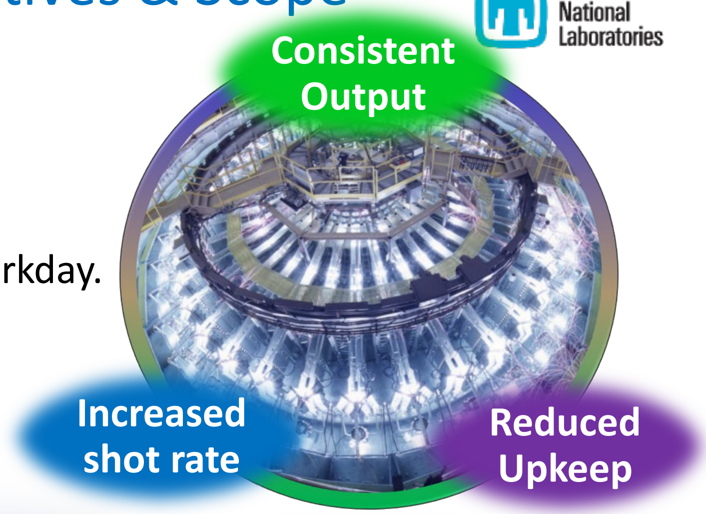
  ~ 40 are potential single point failures that would impact operations for more than a month.

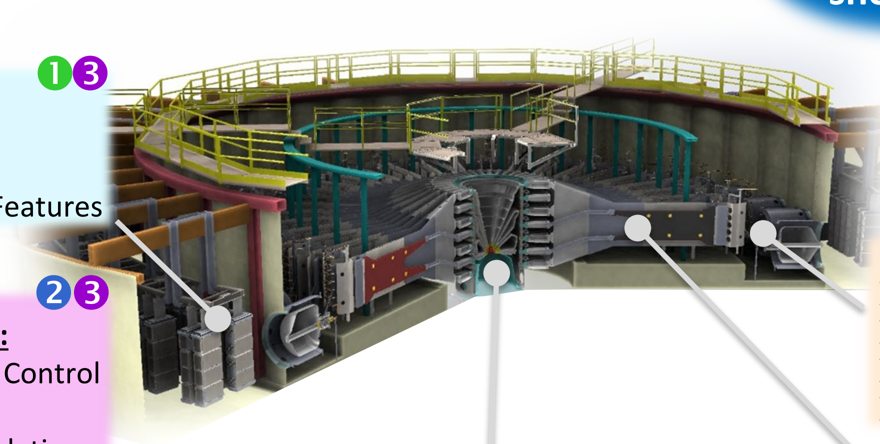
- Sandia (DOE/NNSA) is implementing an ~$49M investment to recapitalize the facility. Activity will occur over 4-5 years.
- Phase 1 activity (~ $30M investment) has begun and will continue to 2024, with 9 month downtime from Q3 2023 – Q2 2024.

Saturn Recapitalization Project: Primary Objectives & Scope

Sandia National Laboratories

1. Provide Consistent Radiation Output
   Radiation output to ~ 10% shot-to-shot variation
2. Increase Facility Shot Rate
   Enable consistent execution of one shot per 10-hour workday.
3. Reduce Time Needed for Facility Upkeep
   Enable routine evaluation of machine performance.





Energy Storage Section: (1)(3)
- Upgrade MTGs
- Laser Trigger MTGs
- Z-Based Operational & Safety Features

Technical Utility Systems: (2)(3)
- Improve Water/Oil Fill & Drain Control
- Stainless Steel DI Water Piping
- SF6-Based Components Gas Isolation
- 24 VDC Water/Oil Actuators, Controls

Facility: (2)(3)
- 8-Ton Crane
- MITL Fixtures Improvements
- Dry Compressed Air
- Paint High Bay
- Access Control System Enhancements

Stack/Vacuum Power Flow Section: (1)(2)(3)
- Improve MITL Alignment & Concentricity
- Design Hard-Set Diode
- Reduce Inductance
- Incorporate Stack Debubbling System
- Stainless Steel MITLs
- Stack & MITL Current/Voltage Monitors

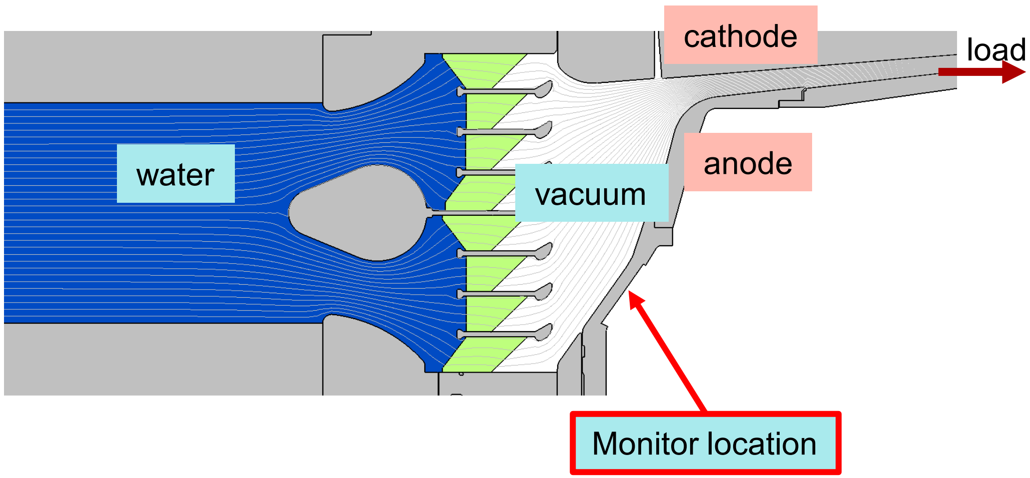
Pulse Forming Section: (1)(2)(3)
- New Triggered Gas Switch
- Improve Gas Switch Trigger System
- Stainless Steel Components
- Update Diagnostic Monitors

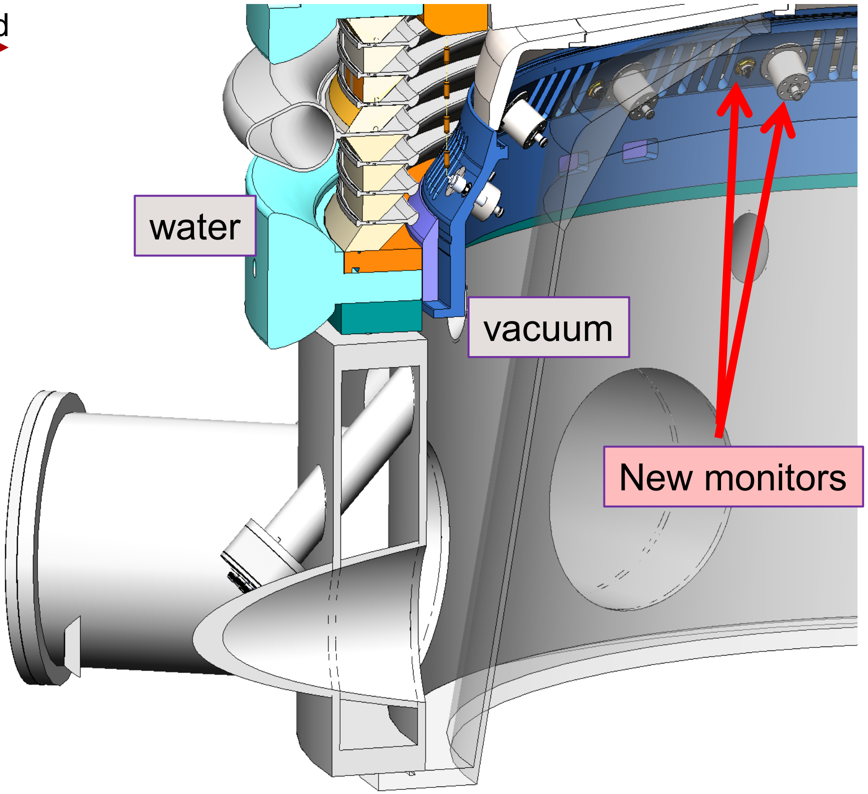
Transmission Section: (1)(2)(3)
- Addition of Water Diverters
- Stainless Steel Components
- Improve Connecting Rod Design

Data Acquisition System: (1)(3)
- Repair/Upgrade Data Ports in Floor
- Fiber Optics Communications Capability
- Stack & MITL Monitors Infrastructure

Some Technical Activity Highlights

Developed and implemented I,V diagnostics to obtain accurate vacuum insulator voltage and forward wave.



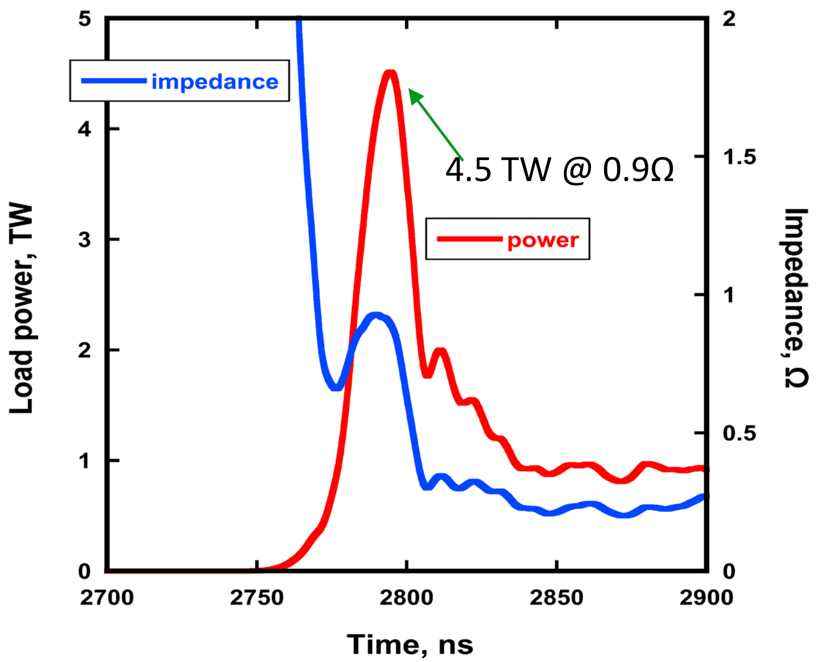


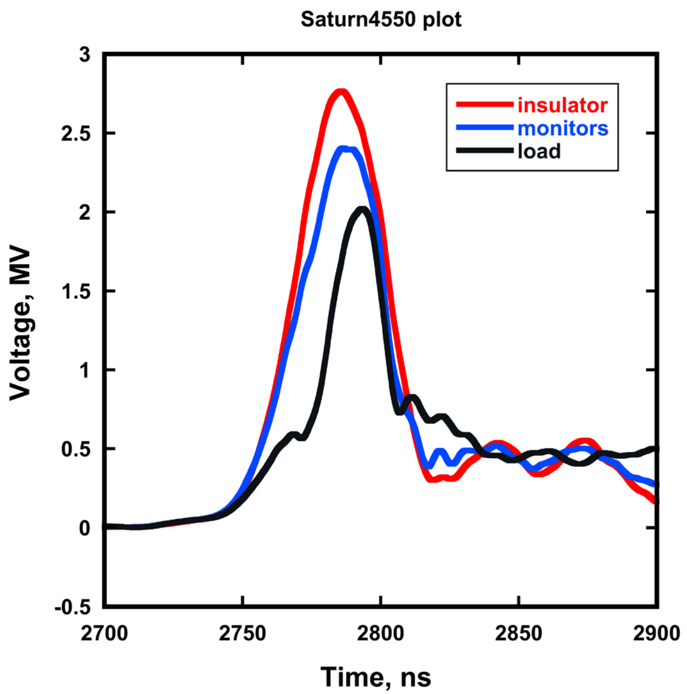
Vacuum MITL flare and monitor locations on lower level anode

- No stable location for monitors exists in the water just outside the insulator
- Voltage and current measurement at the same location
- Modified the lower level MITL flare to accommodate 18 voltage, current monitors in the highest power level of Saturn
  - Current measurement in vacuum is relatively routine
  - Voltage measurement in vacuum requires attention to electron and plasma effects

I,V measurements inform stack and load characteristics.

- Measurement corrected and translated to the insulator stack and load via TEM model (linear, analytic)
- Insulator stack peak voltage ~2.7 MV
- Power on the lower level ~ 4.5 TW and 0.9 Ohm.
  - Translates to outer ring (lower two levels) diode power, impedance ~ 9 TW, 0.45 Ohm
- Observe impedance increase during power pulse rise.
  - Expect increased diode inductance during beam pinch

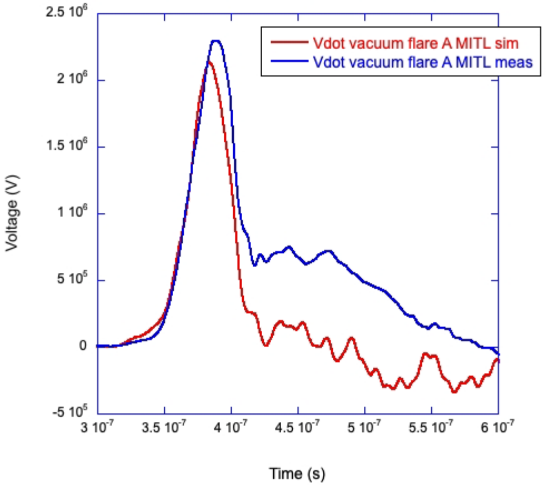


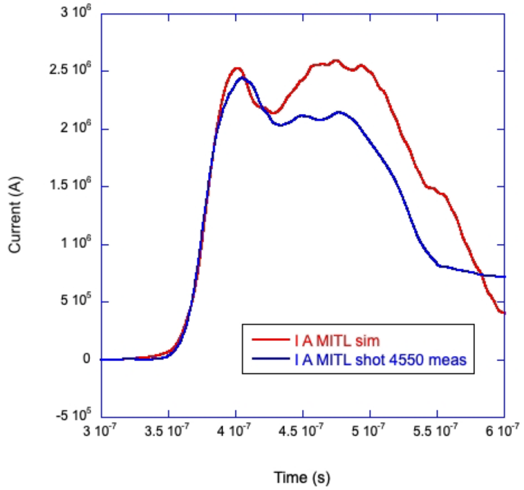


Circuit models and power-flow simulations are aiding design.

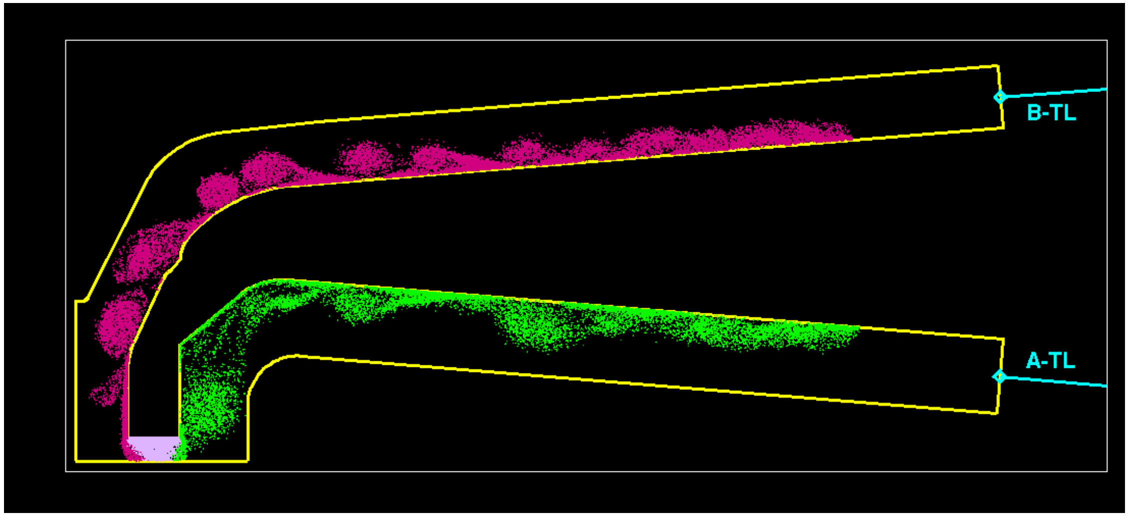
- 3D circuit model uses a separate drive for each of the 36 lines that can be varied in time to investigate timing jitter effects. There is a separate model for each of the 3 cathode levels.

- 2D and 3D EM-PIC models using the EMPIRE code are being used to investigate Insulator stack stresses and MITL power-flow.





Bertha circuit model.



EMPIRE power-flow simulations of lower cathode (A,B levels) and diode.

New output Gas Switch (D1) is in design and test

36 Saturn output gas switches

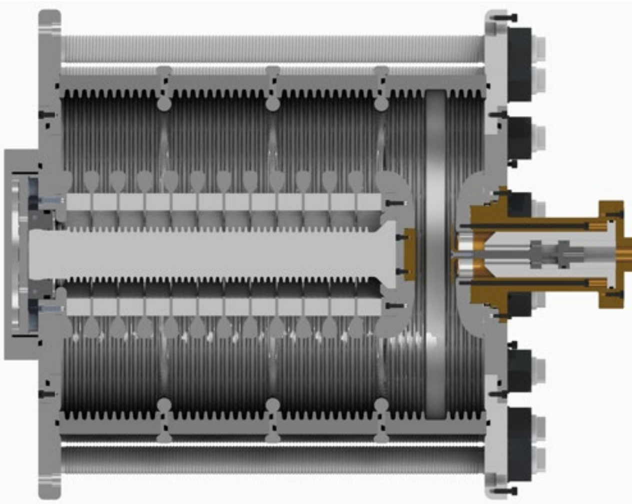
immersed in the Saturn DI water section

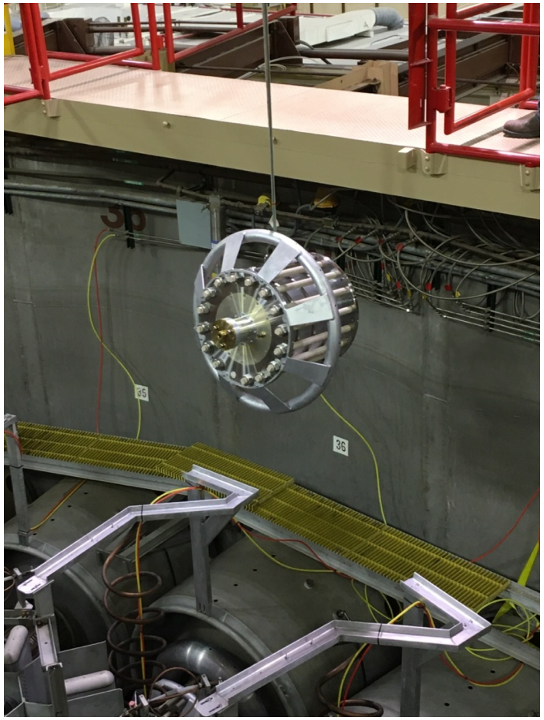
pressurized with SF_6

Tolerate ~2.6 MV before closure

Electrically triggered with a ~80 kV forward wave in high voltage cable

Saturn D1 Switch





Requirements

- Improve jitter to ~ 4ns, 1σ
- Reduce pre-fire rate
- Maintenance lifetime of ~200 shots
- Retain electrical triggering for simplicity, with option to laser-trigger if needed

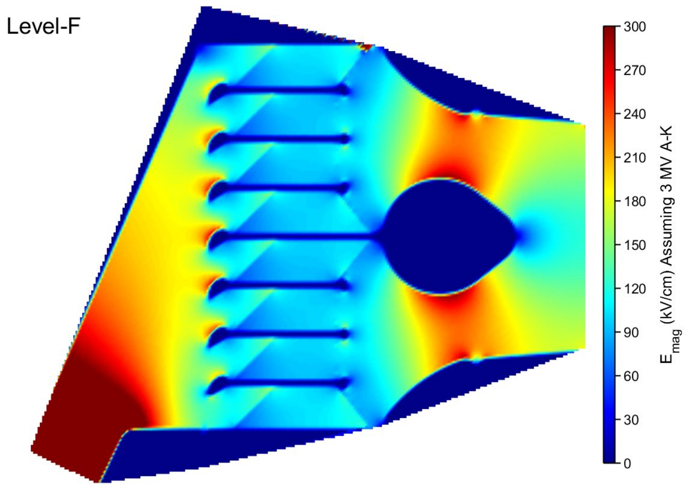
Presently manufactured two switches and installed in Saturn for testing

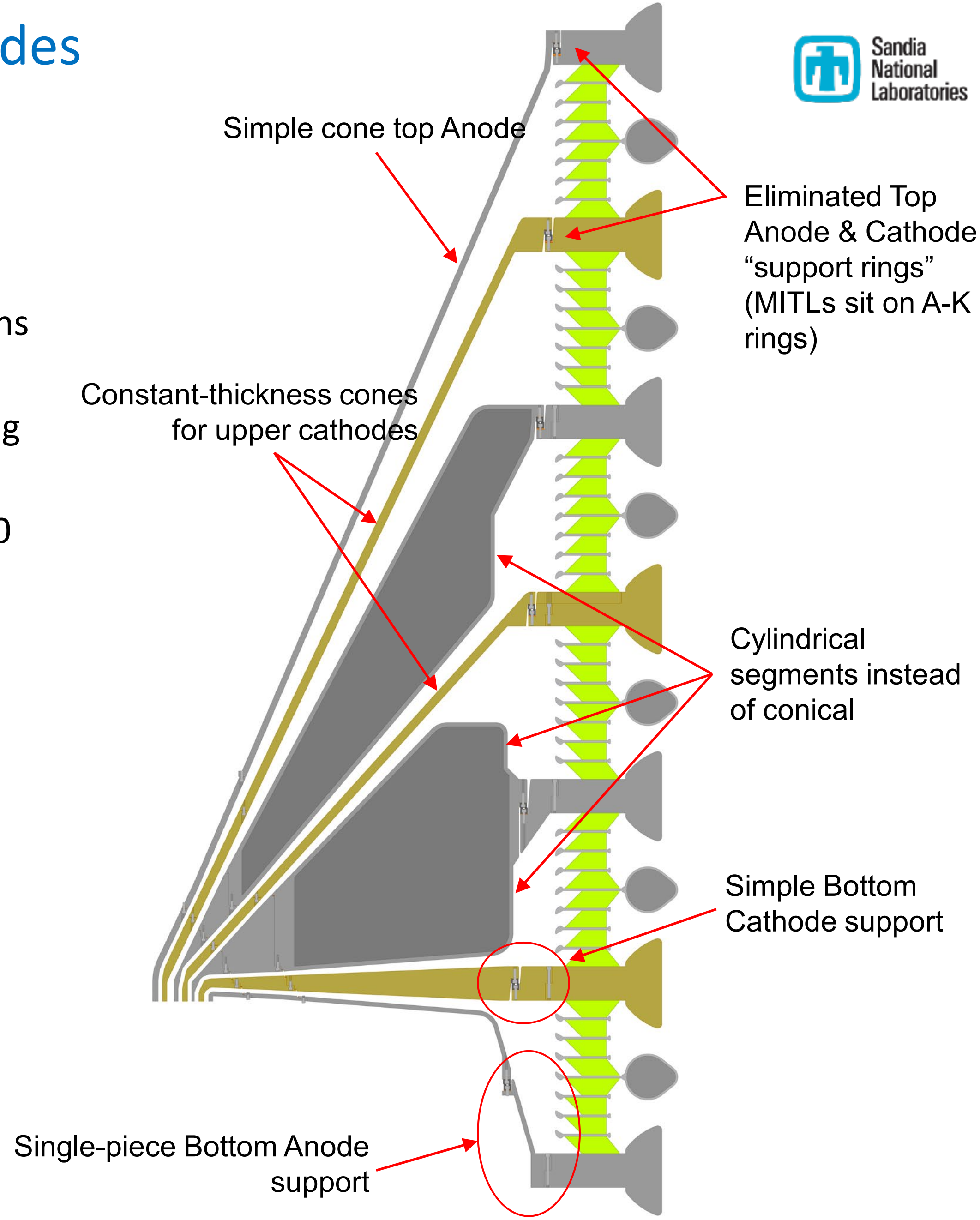
MITL and Insulator Stack upgrades

Design simplifications

- All electrodes made of Stainless Steel (presently mix of SS and Al)
- Eliminated Cathode and Anode variable position support rings to better fix positions with flanged interfaces
- New-simplified electrode shapes, balancing inductance
- Peak E-field on insulator not to exceed 300 kV/cm

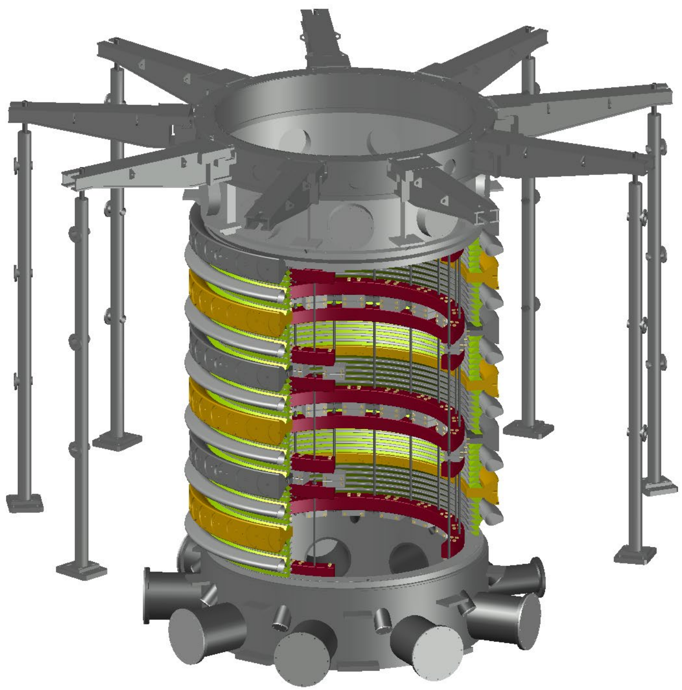
Upper level E-field strength



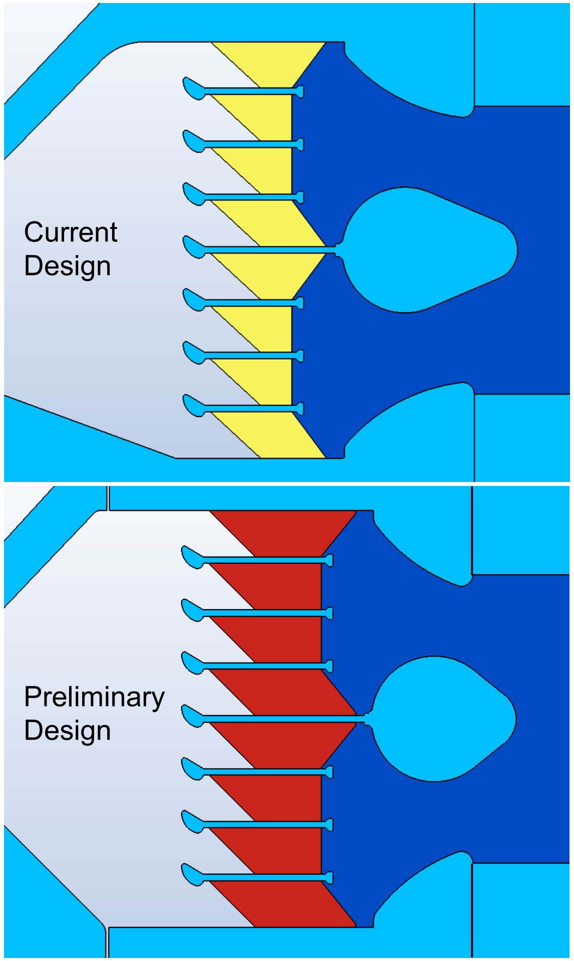


Insulator Stack Geometry Changes

- Increase the width of the insulator rings to provide mechanical stability and room for new voltage and current diagnostics.
- Minimize/eliminate any changes to the water section.
- Propose holding the OD of the AK rings constant, by shrinking the width of the water flare.

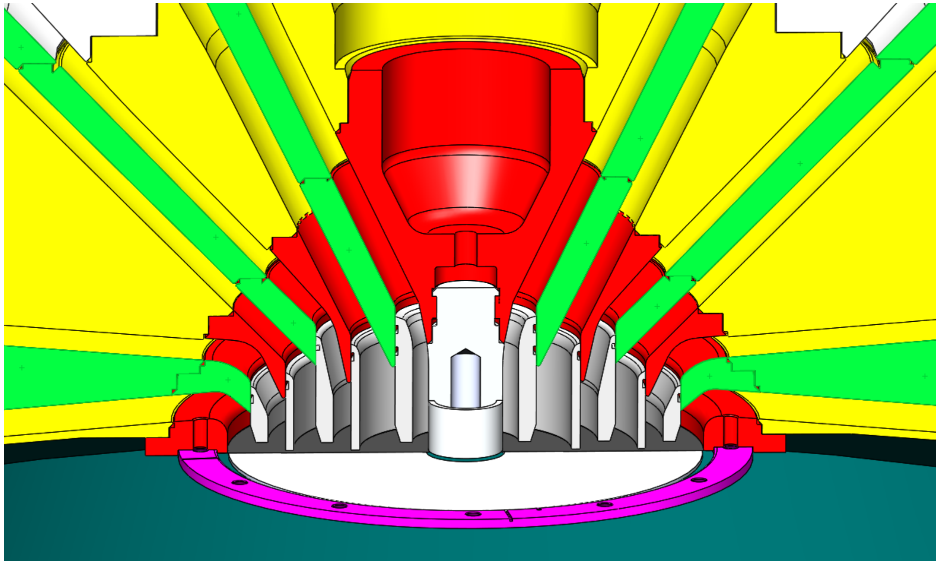


Insulator stack assembly



Standard 3 ring diode on Saturn – three nested annular diodes for low inductance, low impedance

- Diode is comprised of three nested annular triaxial diodes
- Ratio of radii 3:2:1
- Equal widths so ratio of areas 3:2:1
- At the diode, typically 10 MA, 1.6 MV (power weighted mean voltage), 22 ns fwhm radiation pulse



Diode Impedance Optimization

- Goal to limit shot-to-shot radiation output variation
- Dose varies ~ linearly with energy. Assuming the forward voltage V_M is related to the MITL inductance L, load impedance and voltage R, V_L via

$$V_M = V_L + L \, \frac{d\left(\frac{V_L}{R}\right)}{dt}$$

- To first order*

$$D \sim V_L I \tau = \frac{{V_M}^2 \tau}{\left(1 + {L}/{2R\tau}\right)^2 2R}$$

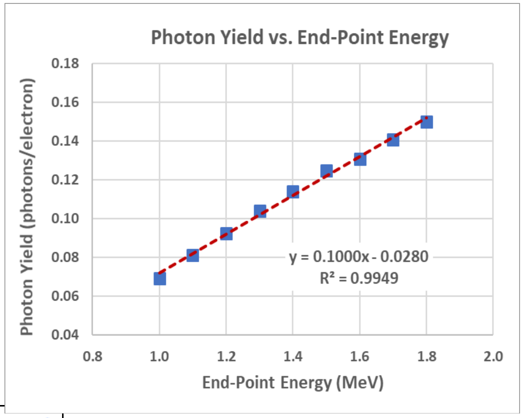
- For each diode ring (MITL level), there is an optimum impedance to maximize output AND minimize variation

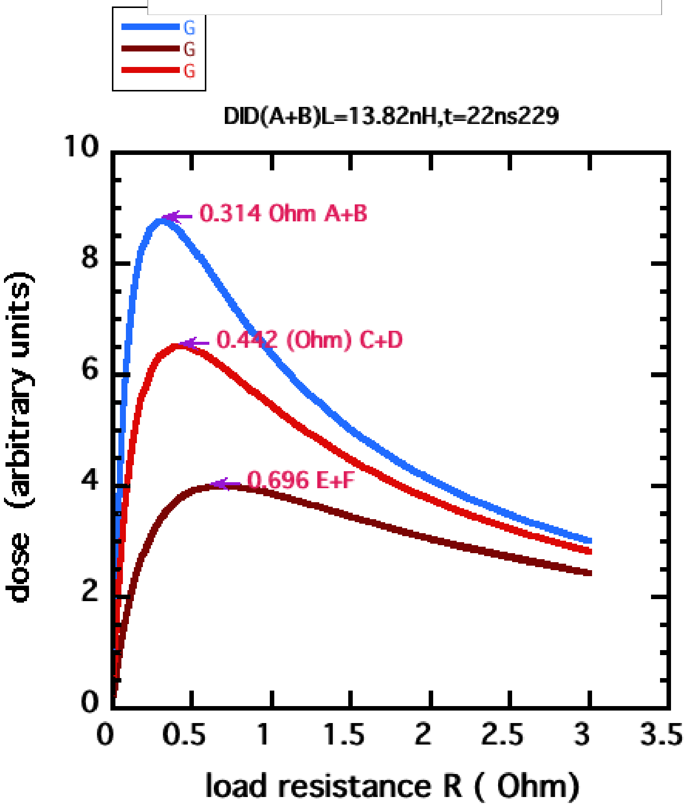
$$\left(\frac{\delta D}{D}\right)^2 = 2^2 \left(\frac{\delta V_M}{V_M}\right)^2 + f(R)^2 \left(\frac{\delta R}{R}\right)^2 + f(\tau)^2 \left(\frac{\delta \tau}{\tau}\right)^2$$

$$f(R) = \left[1 - \frac{2}{\left(1 + \frac{L}{2R\tau}\right)}\right] \text{ and. } f(\tau) = \left[1 + \frac{2L}{2R\tau}\left(\frac{1}{1 + \frac{L}{2R\tau}}\right)\right]$$

- Operate at f(R) = 0, total diode impedance R ~0.1 Ohm

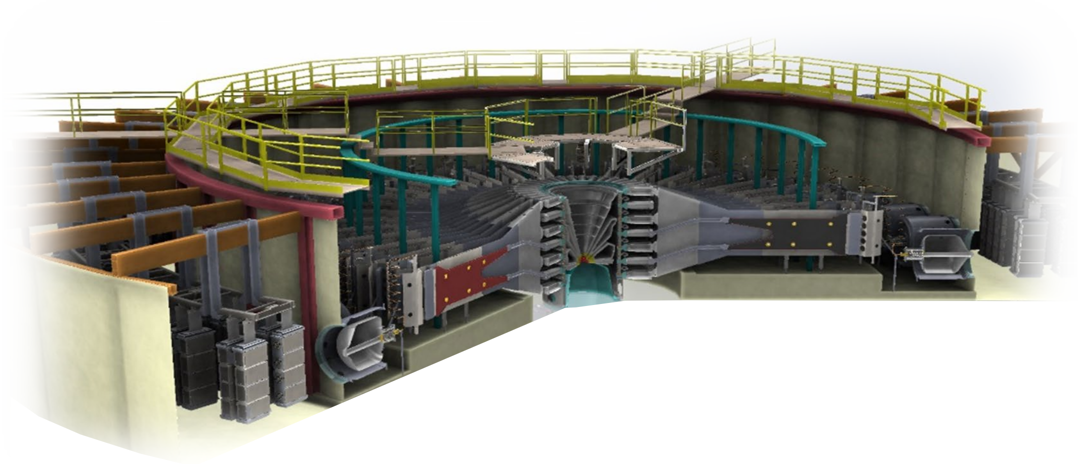
*assumes $dR/dt << dV_L/dt$





Summary:

- Sandia is executing a multi year effort to refurbish and recapitalize major components of the Saturn Accelerator
  - Provide Consistent Radiation Output
  - Increase Facility Shot Rate
  - Reduce Time Needed for Facility Upkeep
- Phase 1 is concentrating on the vacuum section (diode, MITL, stack), high voltage output Gas Switch, as well as additional infrastructure (data acquisition, crane, oil/water)
- Phase 2 will concentrate on the energy storage system (Marx, Transmission, I-store)



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